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ARMSTRONG LABORATORY

FORCE REFLECTING EXOSKELETON (FREFLEX) WORKSPACE MAPPING

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FOR THE COMMANDER

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Determining a robot's reachable volume is important both for operator safety and for ease in the design and specification of experiments. This was the main focus in establishing the workspace for the Force REFLecting EXoskeleton (FREFLEX). Cartesian position data are collected by maneuvering the FREFLEX pistol grip manually. A program written in C first collates these coordinates into "slices" of data. Then, a second algorithm determines the outer boundary of each slice. Stacking the adjusted data slices together provides a clear definition of the maximum FREFLEX boundaries. Additional graphical manipulation through workspace rotation enhances both the view and worker understanding of the FREFLEX work area.

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PREFACE

This research was conducted from August 1993 through March 1994 by the Human Sensory Feedback for Telepresence group in AL/CFBA. Two individuals served as project managers: Capt David K. Nelson (Aug 93-Sept 93) and 1st Lt Barry O. Hill (Oct 93-Mar 94). Acknowledgements are offered to Bob Bolia of Systems Research Laboratories Inc. for developing and writing the algorithms utilized during this project.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

When working with robotic systems, it is useful to know the robot's reachable volume and configurations. The reachable volume may be defined as the sum of all positions in cartesian space that the robotic end-effector can achieve. The robot's arm configurations may be defined as the various joint orientations to which the arm must be driven as it reaches throughout its workspace.

These parameters are of interest because we need to know what orientations the exoskeleton arm can achieve and what its overall volumetric configuration looks like. Having a visual idea of these parameters will aid in the efficient use and design of experiments for the Force REFLecting EXoskeleton (FREFLEX). This will enable specification of the practical work volume, limitations of the workspace due to kinematic constraints, and the operator's reachable subworkspace. Most importantly, this work will provide a determination of unsafe operating orientations, and establish the limit of safety for both the operator and observers.

PROCEDURE

Collecting Data

Cartesian position information of the FREFLEX's pistol grip was collected without the motors being powered up. To collect position data, the following sequence must occur. The FREFLEX's VME controller chassis and host 486 personal computer (PC) must be turned on. Initially, the PC must download the real-time controller-executable code to the 68030 board housed in the FREFLEX's VME controller chassis. This is done automatically when the PC is powered on. Once the onscreen counter reaches 99 percent completion, the screen prompts the user to reset the 68030 card and hit RETURN to finish the initialization of the controller. Upon successful completion, the host PC boots into the appropriate directory with the program for data collection. The user types RUN and the development display appears. The F10 function key displays the OPTIONS drop-down menu. Moving the cursor to the XYZ DATA COLLECTION entry and returning the carriage initiates the data collection process. A data collection output file is specified and begins once ENTER is pressed. P is the pause key which suspends and reinstates data collection. The cartesian information is then collected by manually moving the exoskeleton through every possible arm configuration including the arm's reachable limits. When a data collection run is completed, the ESCAPE key ends the process. The data are collected at a sampling rate of 210 Hz with the potentiometer values (pistol grip position) communicating over a dedicated line to the controller. These values are converted to cartesian xyz position with 0.1-inch resolution. The collected data file is stored on the PC's hard drive and should be transferred to another system for safe keeping and processing. This procedure of data collection can be reiterated as many times as needed. The data files can be concatenated to develop a single data set that is more complete. The positional information of the pistol grip delineates an irregular volume of space that will be

called the FREFLEX's reachable workspace. To aid in the interpretation of this volume, a series of interactive software programs that segment the raw data file into a form that can be graphically presented was written.

Analyzing Data

The C program *cmpress* takes the random collection of data points and collates them into "slices" of data points. These slices are of user-specified width and may be taken along any coordinate axis. The *cmpress* program uses a self explanatory prompt to guide the user. The following information is needed to execute the program: the input file to be used (the raw data file), the name of the new output file, the cartesian plane in which the slice will be taken, and the minimum and maximum range of values along the designated axis that are to be compressed within the selected plane. The nomenclature used to label the input files for processing is the suffix .dat. All of the raw data points are concatenated within the file called total.dat. The *cmpress* output files are designated by the following form: $X_1X_2X_3X_4.prss$. The first symbol, X_1, identifies the axis (x, y, or z) along which the slice is taken. X_2 indicates the direction (p-positive values or n-negative values) of the slice with respect to the origin. The last two labels define the position of the slice, in inches, from the center of the origin. Each slice is taken in one-inch segments. The number shown is the minimum position from where the slice was taken. For example, the slice between 5 and 6 shows 5 in the file name, while a slice between -12 and -13 displays the lower value of -13 (the negative displayed by symbol X_2 as discussed above).

The boundary points of this slice of information are determined using the *bound1* program. This program can manipulate any raw data file, whether the total raw data file or a slice of raw data from the *cmpress* output. It determines which data points maintain the outer boundary of the volume. First, *bound1* requests the filenames of the input and output files, and follows by opening both. The user is then prompted to select one of the three coordinate planes to consider. For this description, the xy plane is designated. Once the plane has been specified, the data points in the input file are converted to integers (via multiplication by 10 and truncation) and read into an array called alldata[3][12000]. The data, therefore, maintain a 0.1-inch resolution. As the points are read into memory, the minimum and maximum values are calculated for all three dimensions, and a count is taken of the number of points in the file. The input file is then closed. The algorithm loop begins by locating all points having the coordinate $z = min_z$. For each such point, a "1" is placed into a 600x600 matrix, the rows and columns of which correspond to the x and y dimensions. This gives a picture of one slice of the data. Through this slice of data, two passes are made as shown in Figure 1. Each pass stops at the first point found in each row or column and assigns a negative value (-1) to its position in the matrix. Following the passes, the points found are converted back to floating point numbers and written to the output file. This procedure is followed $(max_z - min_z)$ times, because all slices are taken at one-inch intervals. Then, the output file is closed and the program is exited. The output of this program is an ordered list

of points that roughly approximates the perimeter of their volume. The nomenclature that has been used to label the boundary files uses the suffix .bnd. The naming of the boundary output file is the same as that used by the *cmpress* program.

A second algorithm, *bound2*, was also written. This program resembles *bound1* exactly except for one detail. *Bound2* makes two scans from the two sides not utilized in the other program. These two passes are made along the sides parallel to the operator's position. This can be seen in Figure 2. A visual comparison between the plots showed that *bound2* resulted in a loss of accuracy and detail of the maximum boundaries. Therefore, it was decided to use only *bound1* for determining the outer regions of the workspace.

The plot of the *bound1* output file graphically shows a contour of the workspace volume for a specific slice in elevation. The contour is not a smoothed boundary due to the fact that, in data collection, the motion of the exoskeletal arm is randomly chosen. Therefore, the contour displays a jagged perimeter since not all boundary points are available within an elevation. Also, this boundary search method cannot correctly resolve a concave-shaped boundary in a slice. In order to deal with these problems, two similar, yet separate, adjustments were made to previous algorithms to achieve success with this final *bound1* program.

To correct for the irregular perimeter, an adjustment was made to the resolution, allowing the user to specify the level of resolution desired in increments of one-tenth inch up to 1.9 inches. Increasing the resolution eliminates most of the interior points which, when plotted, cause the jagged appearance. Instead, only the outermost points are plotted, forming a smoother contour of the slice. A drawback remains in the possible loss of accuracy incurred by this program. Some of the gaps eliminated may actually exist at that area in the workspace. Additional, more extensive work would be necessary to verify the existence of this problem.

To adjust the concavity at the corners, the original seven-scan algorithm was adjusted to scan only twice from opposing sides. As described above, each scan stops at the first point found in each row or column. The problem was apparently the inability of the plotting program to correspond with the selected data points. The program maintained an ordered, numerical pattern while plotting by connecting each point in the order in which it was read. Points from one scan were all connected before those located from another. Therefore, the first point read by a scan is often numerically closer to mid-points located in the previous scan than to the final one. However, the plotting program was unable to incorporate the first point of the subsequent scan into the plot until connection of the preceding points was complete. This resulted in erratic patterns around the edges (corners) of the plot. By utilizing only two scans, these rough configurations were eliminated; however, it was not possible to replicate complete concavity within the plots.

The entire workspace height was determined to be approximately 50 inches. With respect to the origin, this area extended 25 inches below the center position (negative direction), and 25 inches above the origin (positive direction). Fifty one-inch slices were taken of the workspace, and then

run through *cmpress* and *bound1* respectively. Then, by plotting the contour lines consecutively, a 3-D shell of the FREFLEX's reachable workspace was better represented. The graphical program, Gnuplot 3.5, does not implement hidden lines, which adds to the uncertainty of the interpretation. However, the plot is clear enough to provide reasonable clarity of the workspace. A 2-D graph of each separate plane of view for the workspace provides for the best determination of the actual size and measurements of this area.

DATA

The first group of plots is documented in the text. These aid in the explanation of the algorithms and methods used to map the workspace. The final set of graphs (Figures 3-9) displays the initial representation of the entire workspace area of the FREFLEX. The plots are shown consecutively in 30-degree increments of rotation for a 180-degree turn, establishing a solid description of the workspace region.

RECOMMENDATIONS

First, more data must be gathered from the FREFLEX. Additional data will fill in many gaps in the present plots, will aid in eliminating unwanted interior points, and thereby improve the visual details of the workspace.

The final step will eventually be to map an individual's reachable workspace as a subworkspace of the exoskeleton's. This experiment should utilize gravity compensation to provide an easier task for the operator. Once the individual's reachable workspace is determined, the amount of useable exoskeleton workspace will be known. These two parameters are needed in order to specify many things about the exoskeleton. They will delineate the volume that is useful for experiment design, graphically display the orientations and areas that must be guarded against being reached due to potential operator harm, and aid in identifying any present kinematic design limitations which could be rectified in a next-generation exoskeleton.

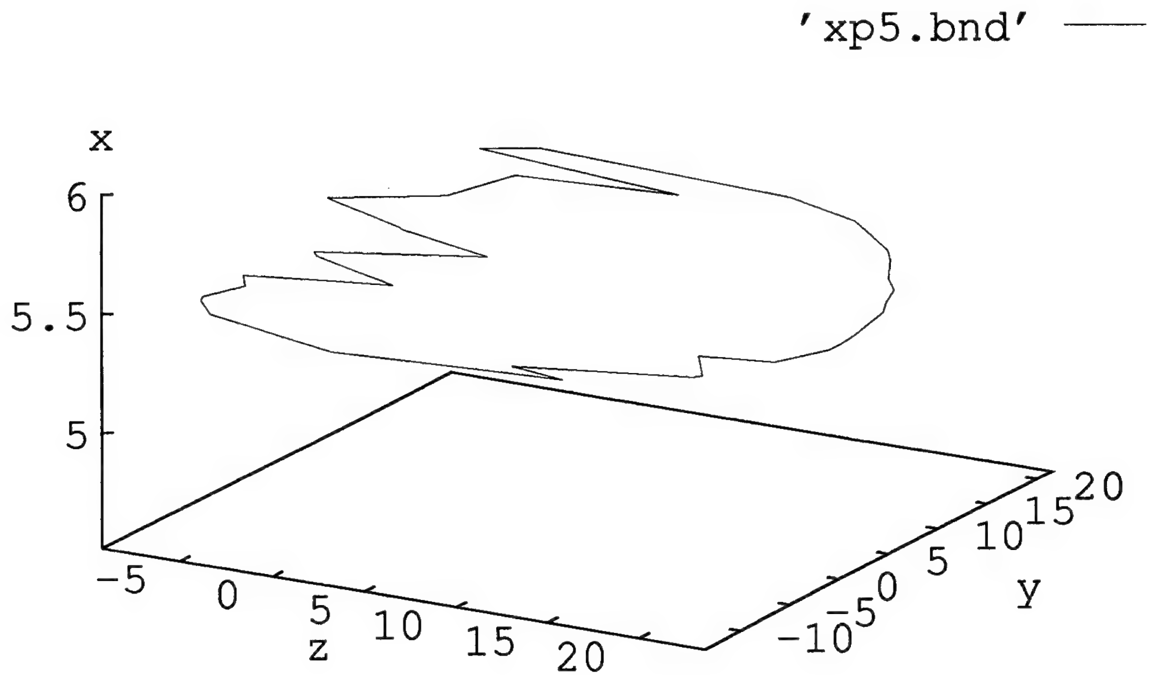

Figure 1. Data slice utilizing algorithm *bound1*.

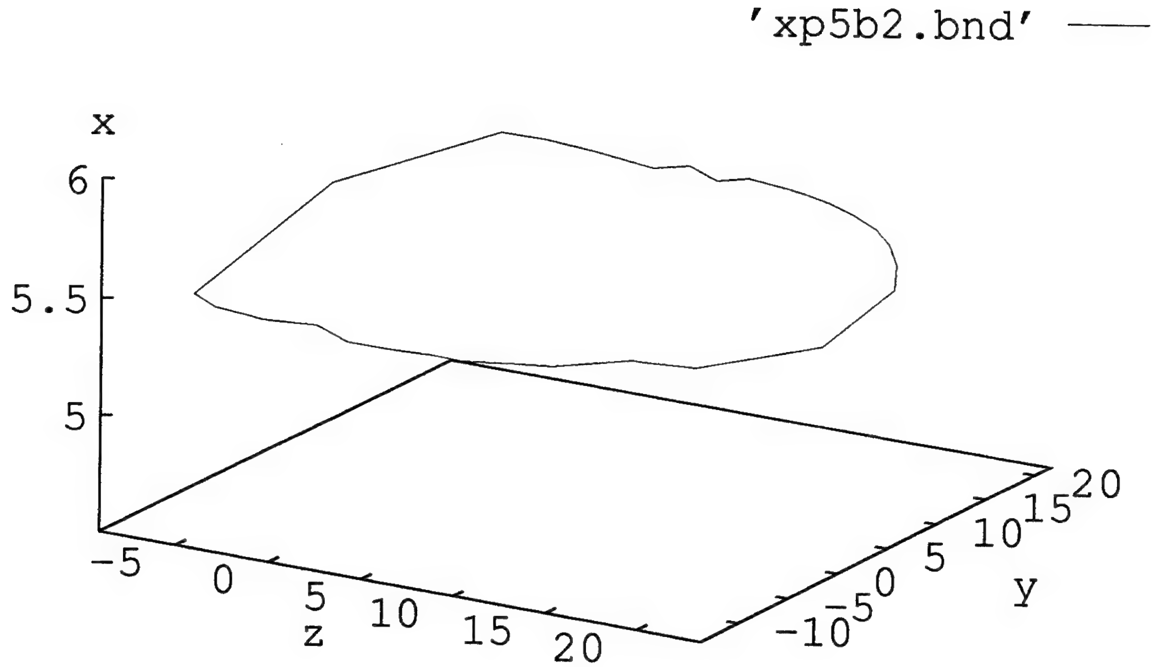

Figure 2. Data slice utilizing algorithm *bound2*.

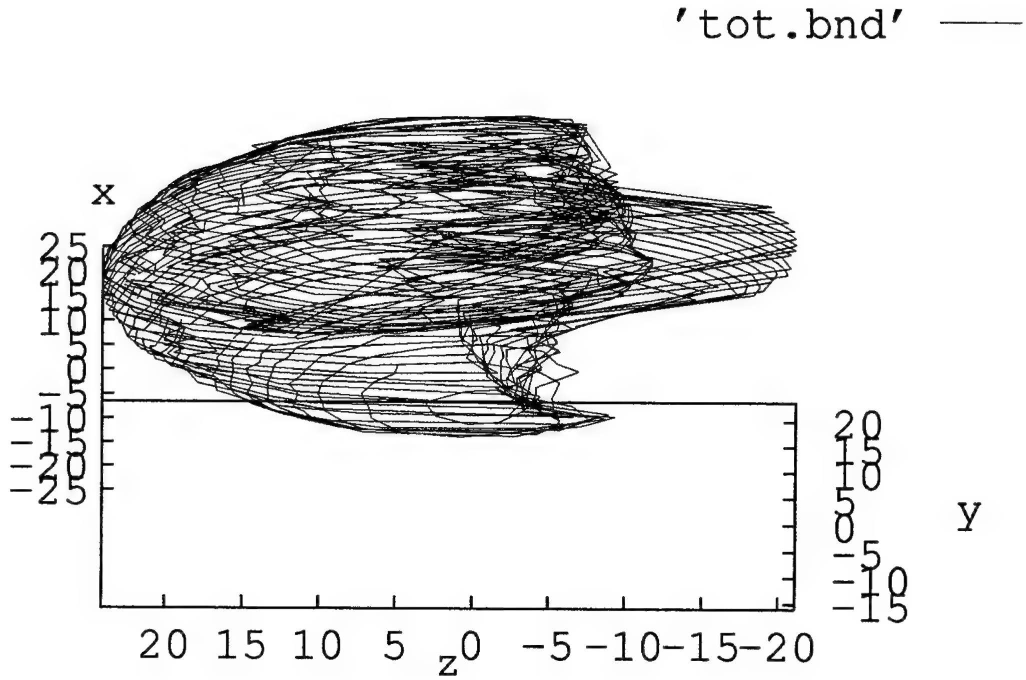

Figure 3. FREFLEX Workspace: 180 degrees on z-axis.

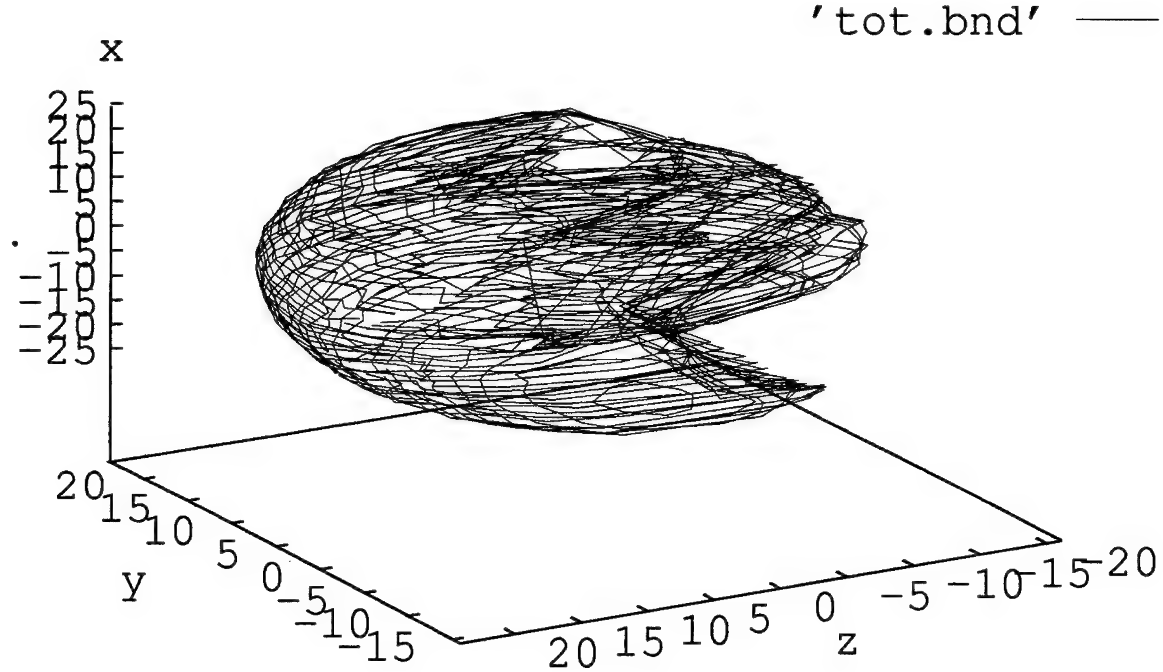

Figure 4. FREFLEX Workspace: 210 degrees on z-axis.

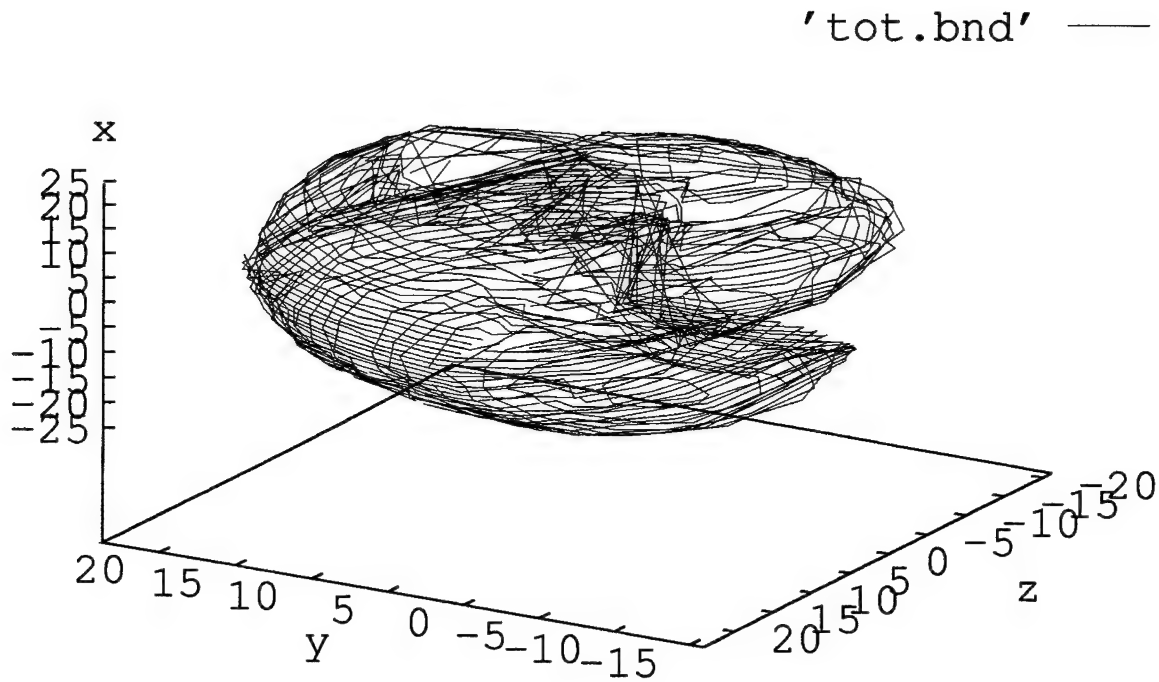

Figure 5. FREFLEX Workspace: 240 degrees on z-axis.

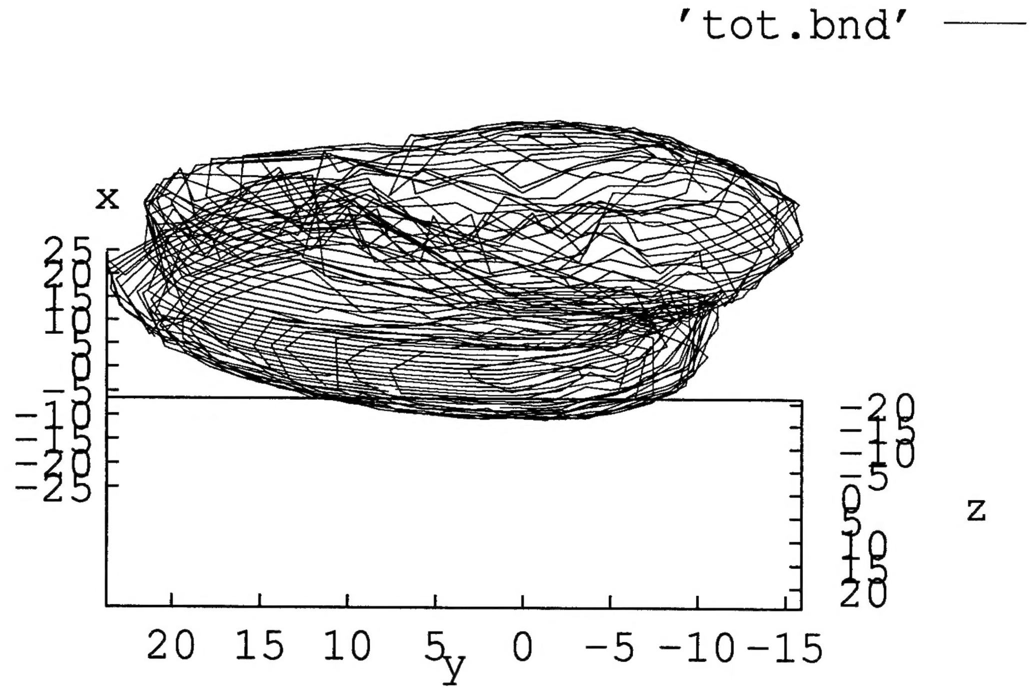

Figure 6. FREFLEX Workspace: 270 degrees on z-axis.

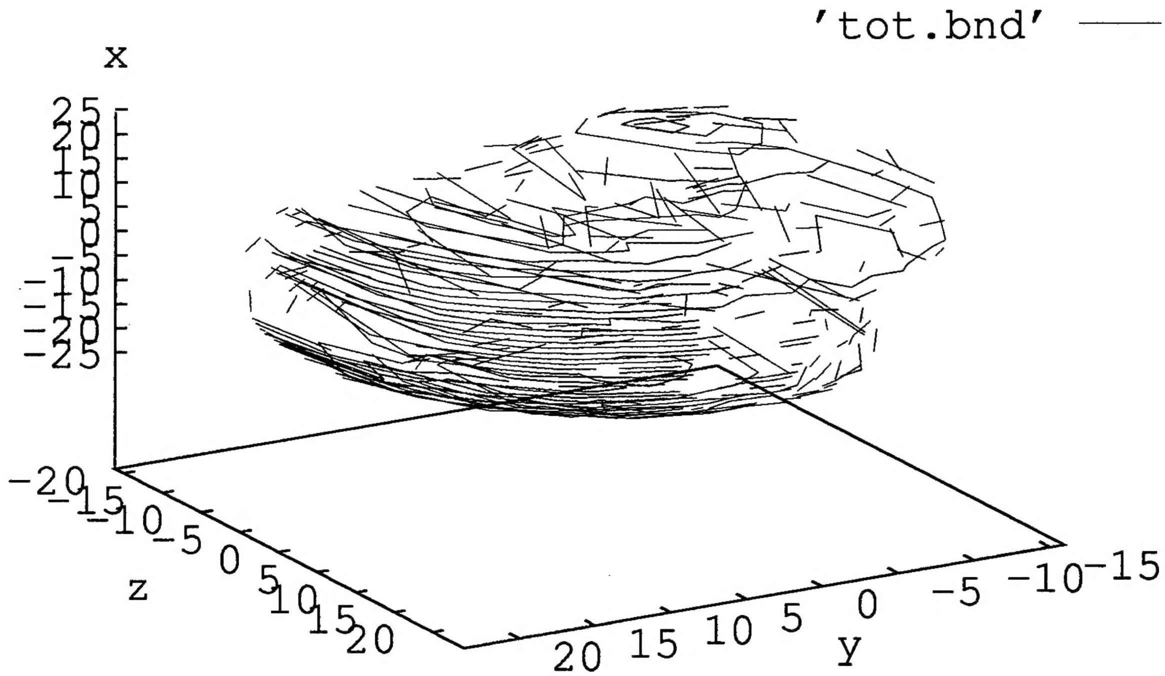

Figure 7. FREFLEX Workspace: 300 degrees on z-axis.

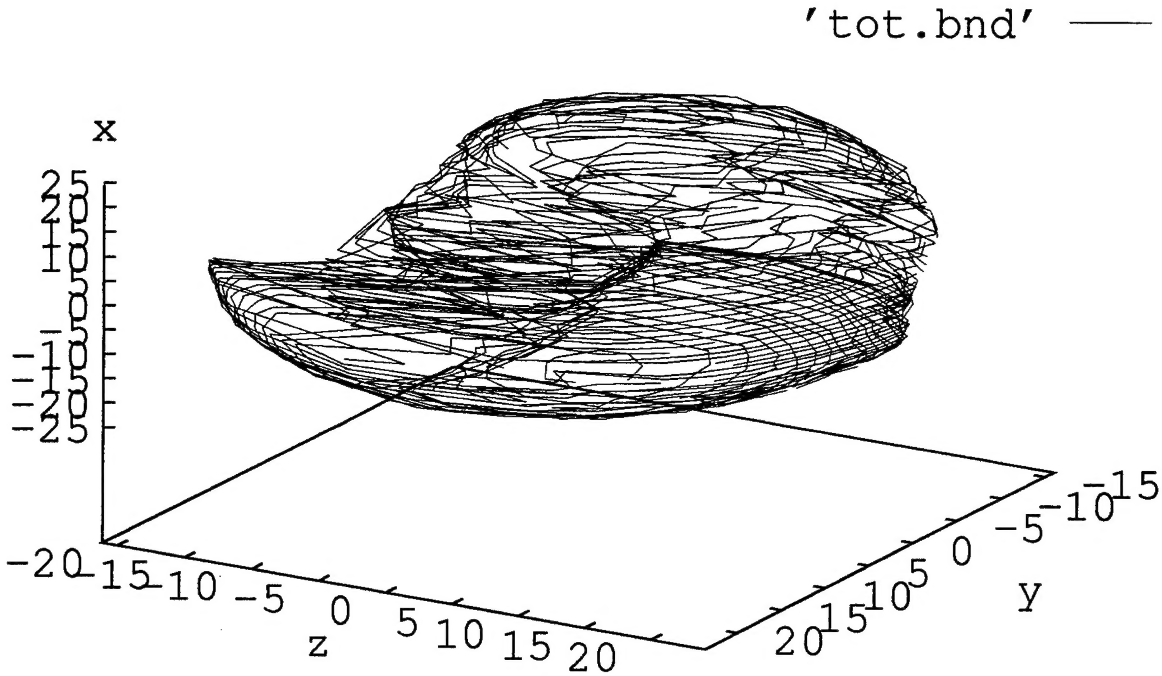

Figure 8. FREFLEX Workspace: 330 degrees on z-axis.

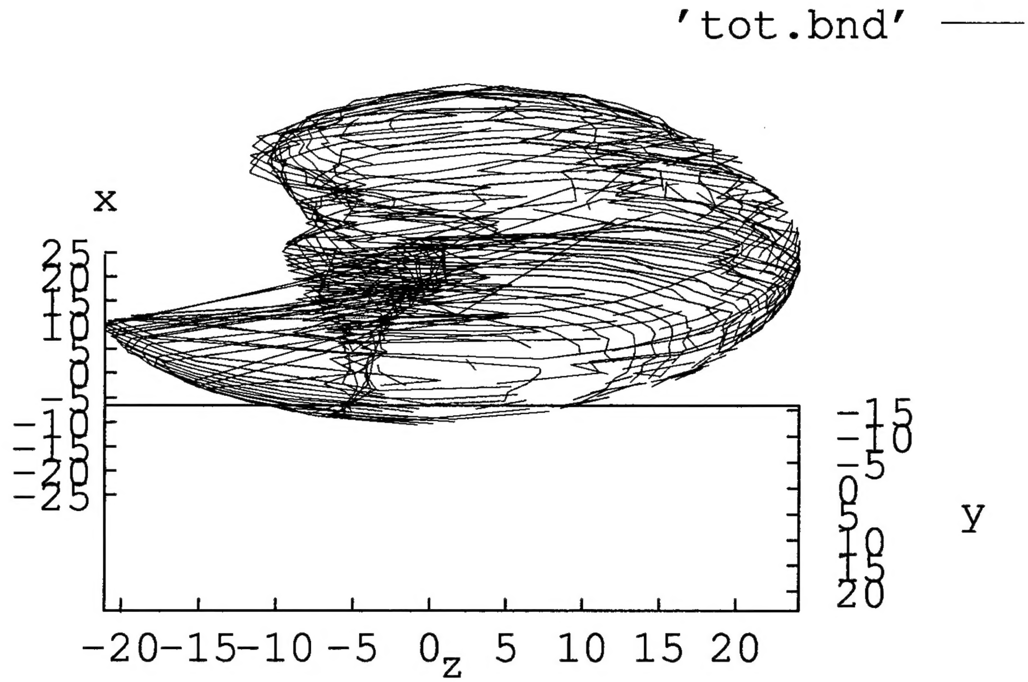

Figure 9. FREFLEX Workspace: 360 degrees on z-axis.

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